

18<sup>th</sup> CRC ON-ROAD VEHICLE EMISSIONS WORKSHOP

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# FINAL RESULTS FROM CARB'S EVALUATION TESTING OF THE EUROPEAN REFERENCE VEHICLE FROM THE PARTICULATE MEASUREMENT PROGRAM

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## Driver of the European Particulate Measurement Program (PMP)

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- There is growing concern that ultrafine particles may pose adverse effects on human health.
- Mass-based PM emission standards regulate larger size particles.
- There is a need for new particulate emission measurement methods to better quantify PM emissions from advanced diesel vehicles equipped with a DPF.

### **PMP Particulate Sampling Methods:**

- The PMP Mass Measurement Methods are similar to the current European and the improved US 2007 methods.
- The PMP Particle Number Measurement Method includes counting only solid particles between 23 to 4000 nm. Volatile particles are removed.



# Euro 5/6 PM Emission Standards

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*European Council has adopted the Euro5/6 emissions standards for light-duty vehicles*

## **Euro 5 Particulate Emission Standards:**

PM Mass: 5 mg/km (PMP Method)

Effective from 2009 for new type approvals; 2011 for all models.  
Required the use of particulate filters on all diesel cars.

## **Euro 6 Particulate Emission Standards:**

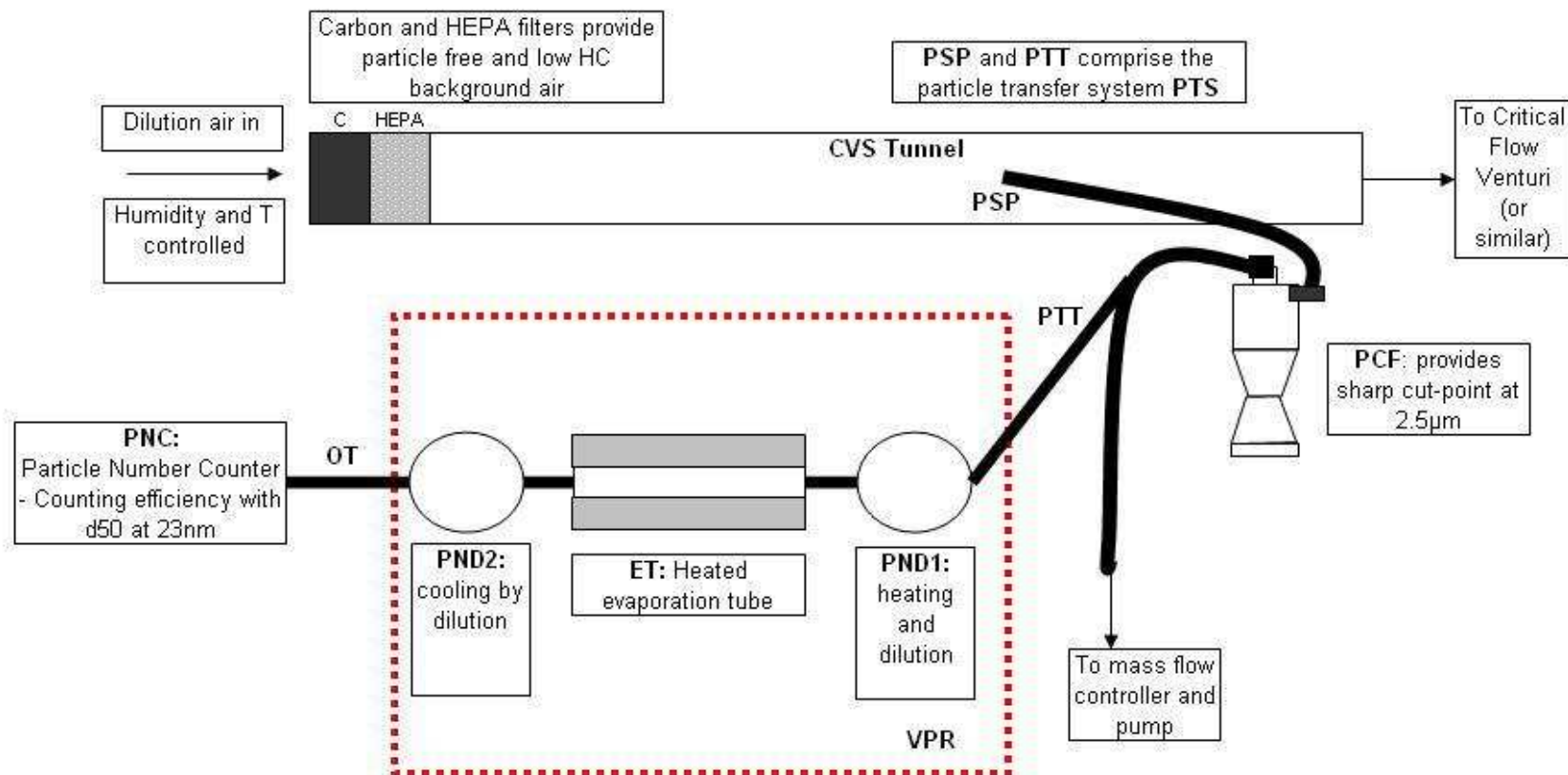
PM Mass: 3 mg/km (PMP Method)

Particle Numbers:  $5 \times 10^{11} \text{ km}^{-1}$  (PMP Method)

Effective from 2014 for new type approvals; 2015 for all models.



# Schematic of Recommended PMP Particle Sampling System\*



**PMP Solid Particles:** *Sampled from the CVS by the measurement equipment, between ~23 nm and 4 μm in diameter, of sufficiently low volatility to survive evaporation after a residence time of 0.2s at 300 °C*

*(Particle Measurement Programmed Light-duty Inter-Laboratory Correlation Exercise (LICD\_LD) Final Report)*



# **CARB Testing of the PMP Vehicle and Particle Measurement System**

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**The European PMP was introduced in 17<sup>th</sup> CRC Workshop last year**

- CARB's informal participation in the UN-GRPE PMP Light-duty Inter-Laboratory Correlation Exercise (ILCE\_LD) was arranged under a MOU signed between CARB and Joint Research Center (JRC) of the European Commission's Directorate General.
- CARB and JRC have agreed to collaborate in a number of research areas of mutual interest, such as PM emissions measurement.

**CARB Testing of the PMP method was beneficial to JRC and CARB.**

- For JRC, it provided an important data point independent from the European inter-laboratory correlation program (PMP ILCE\_LD).
- For CARB, it provided practical experience with the PMP methodology and a unique opportunity for comparing test results with other laboratories around the world.



# Golden Vehicle

The GV (Reference Vehicle) was transported from Europe to CARB and tested in CARB's Haagen-Smit Laboratory

## Vehicle Specifications:



Vehicle Class	Peugeot 407 Saloon 2.0 Hdi 136 SE
Vehicle Identification No.	VF36DRHRH21028953
Vehicle Manufacturer	PSA Peugeot Citroen
Engine Type	Diesel
No. of Cylinders	4
Engine Displacement in cm <sup>3</sup>	1997
Transmission Type	6 speed manual
Fuel Delivery	Common rail D.I.
Aspiration	Turbocharged
Fuel Tank Capacity in liters	66
Test Inertia (lbs)	3500
Emission Control System	FAP (uncoated silicon carbide + FBC)
Drive Wheel Tire Type	215/55 R 17 W
Rated Power in kW	100
Max. Speed in km/h	203
Odometer (km)	20200



# Testing Overview

Tailpipe emission testing was performed in CARB's light-duty diesel test cell No. 7.

## Test Cycles:

1. New European Driving Cycle (NEDC)
2. U.S. FTP Cycle
3. PMP Pre-conditioning Cycle

## Test Fuel:

California ultra low sulfur diesel fuel (<15ppm)

## Lubricating Oil and Fuel Borne Catalyst:

Fully Synthetic Low Sulfur (<0.2%) 0W/40 PAO  
Lubricant and Cerium Based Fuel Borne Catalyst  
were Provided by JRC

## Emission Testing:

Gaseous Emissions: CFR compliance CVS sampling system  
PM mass: 40 CFR 1065 compliance filter sampling system  
Particle Number: Multiple systems  
PM Characterization: EC/OC, Metal  
Evaporative Emissions





# Particle Conditioning and Measurement Systems

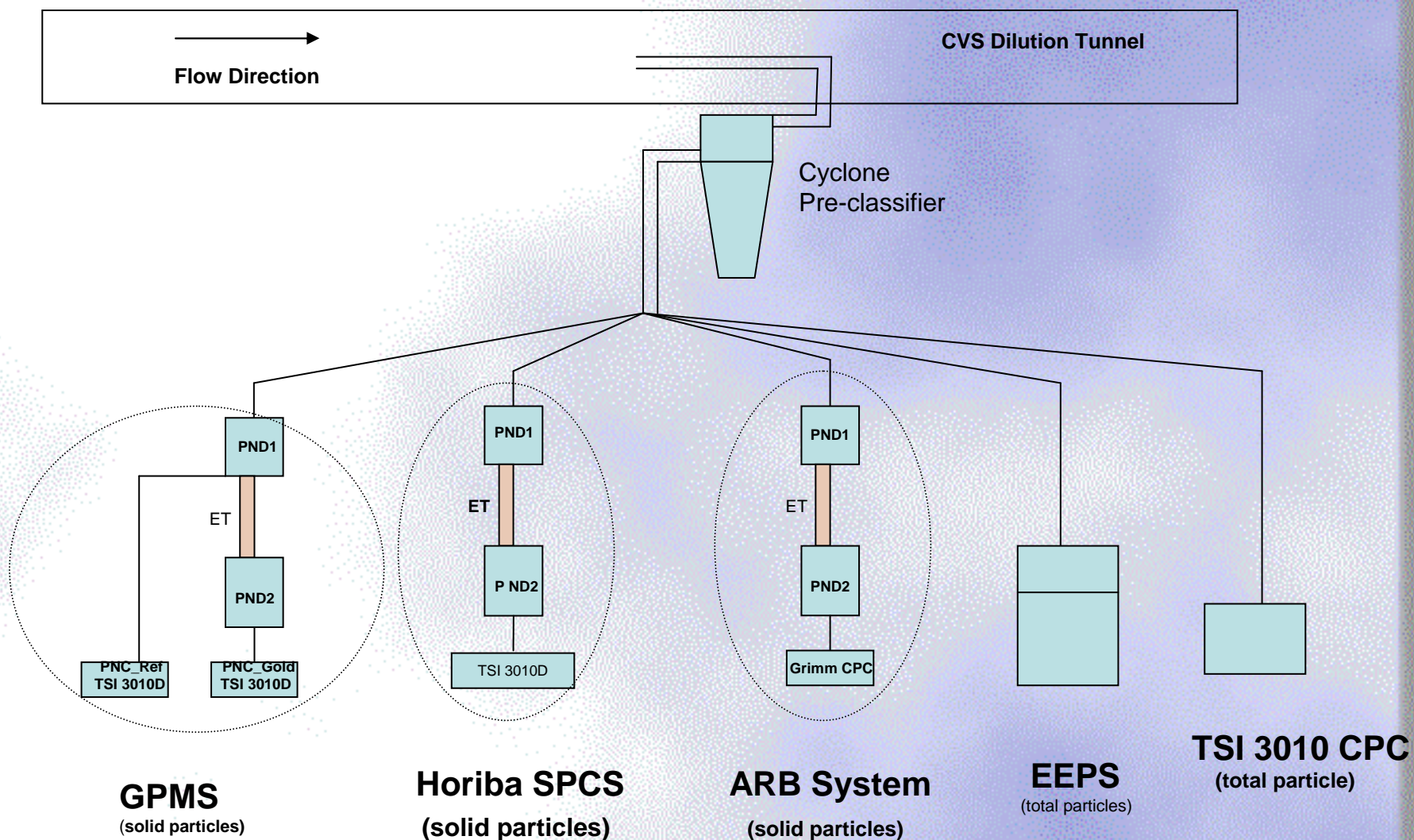
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Several particle number measurement systems were tested simultaneously.

- **PMP Measurement System (GPMS)**
  - Transported to CARB from Europe.
  - Includes:
    - A cyclone pre-classifier: removes 2.5  $\mu\text{m}$  or larger particles
    - A Volatile Particle Remover (VPR): Rotating disc diluter and evaporative tube (MD-19) removes volatile Particles, and secondary diluter to lower aerosol sample temperature.
    - A Reference and a Golden Particle Number Counter (TSI 3010s) count particles  $>23\text{nm}$
- **Horiba Solid Particle Counting System (SPCS) – Meets PMP Requirements**
  - VPR and Particle Number Counter (TSI 3010): counts particles  $> 23 \text{ nm}$
- **CARB's Particle Measurement System:**
  - VPR (MD-19) and Particle Number Counter (Grimm CPC 5.403) - count particles  $> 5 \text{ nm}$
- **TSI Engine Exhaust Particle Sizer Spectrometer (EEPS) – measures particles  $> 5.6 \text{ nm}$**
- **Second TSI Particle Number Counter (TSI 3010) – counts particles  $>10\text{nm}$**



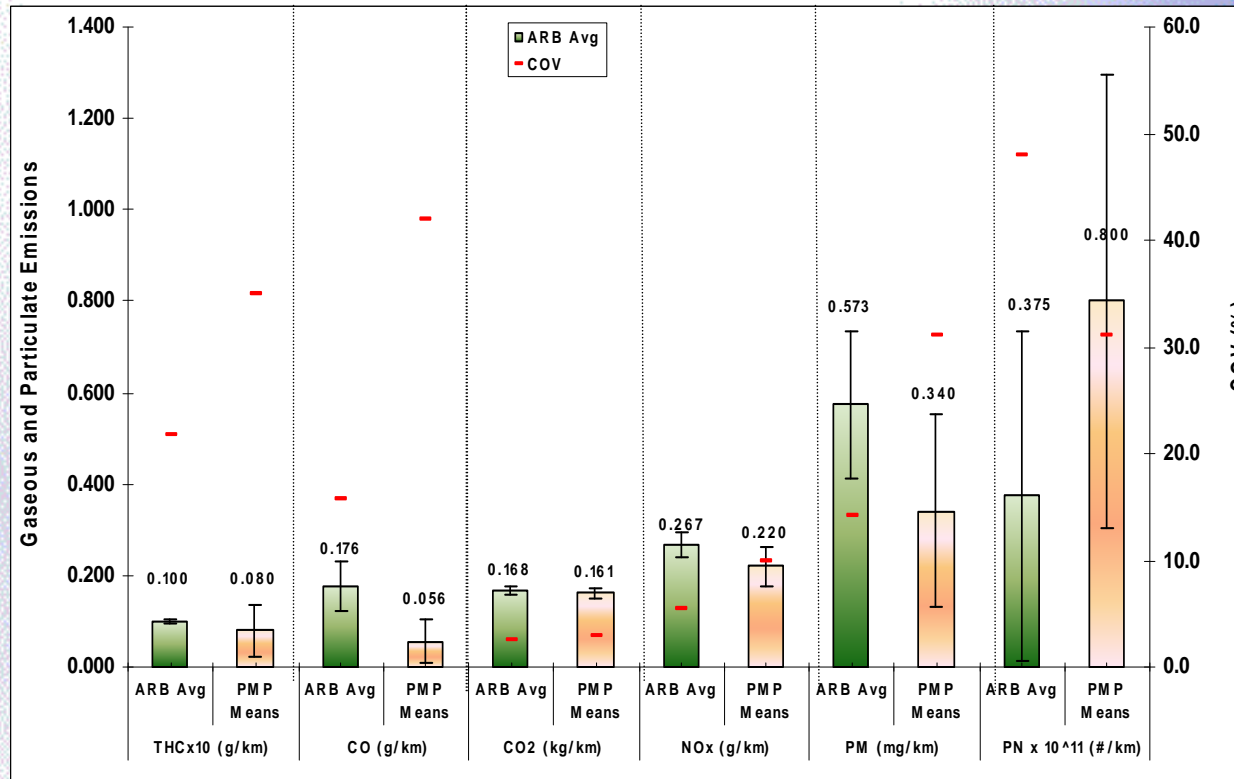
# Schematic of Particle Number Measurement Setup





# Emission Results

## 1. Comparison of CARB and PMP Inter-lab. Mean Results of five NEDCs



- Gaseous Emissions:**

THC, CO<sub>2</sub> and NO<sub>x</sub> are comparable to PMP means. CO is about three times higher.

- Particulate Emissions:**

Avg PM Emissions = 0.573 mg/km  
(PMP Range: 0.2 - 0.6 mg/km)

Avg PN Emissions = 0.375 x 10<sup>11</sup> /km  
(PMP Range: 0.5x10<sup>11</sup> - 1.3x10<sup>11</sup>/km)

CARB results are from the Horiba SPCS

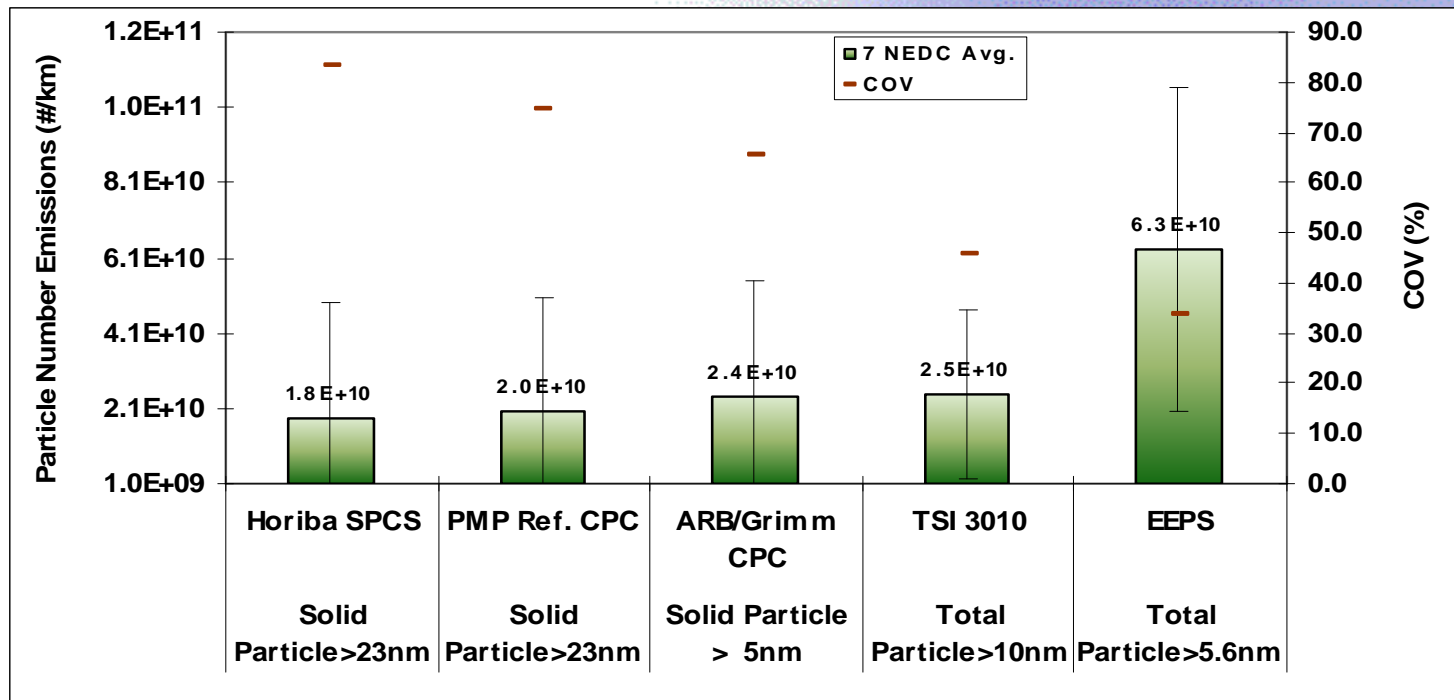
- Coefficient of Variance (CoV):**

In general, the CoVs for both gaseous and PM from CARB are lower than the PMP inter-lab mean. CoV of PN measured from the Horiba SPCS was 47%, within the PMP range of 12-72%.



# Emission Results (cont')

## 2. Comparison of Particle Conditioning and Counting Systems

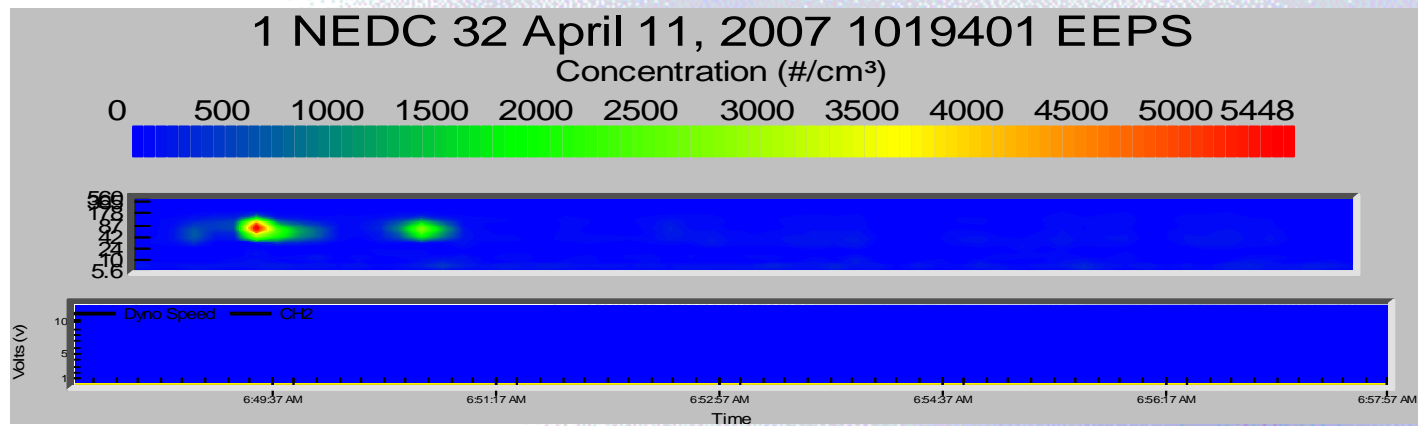
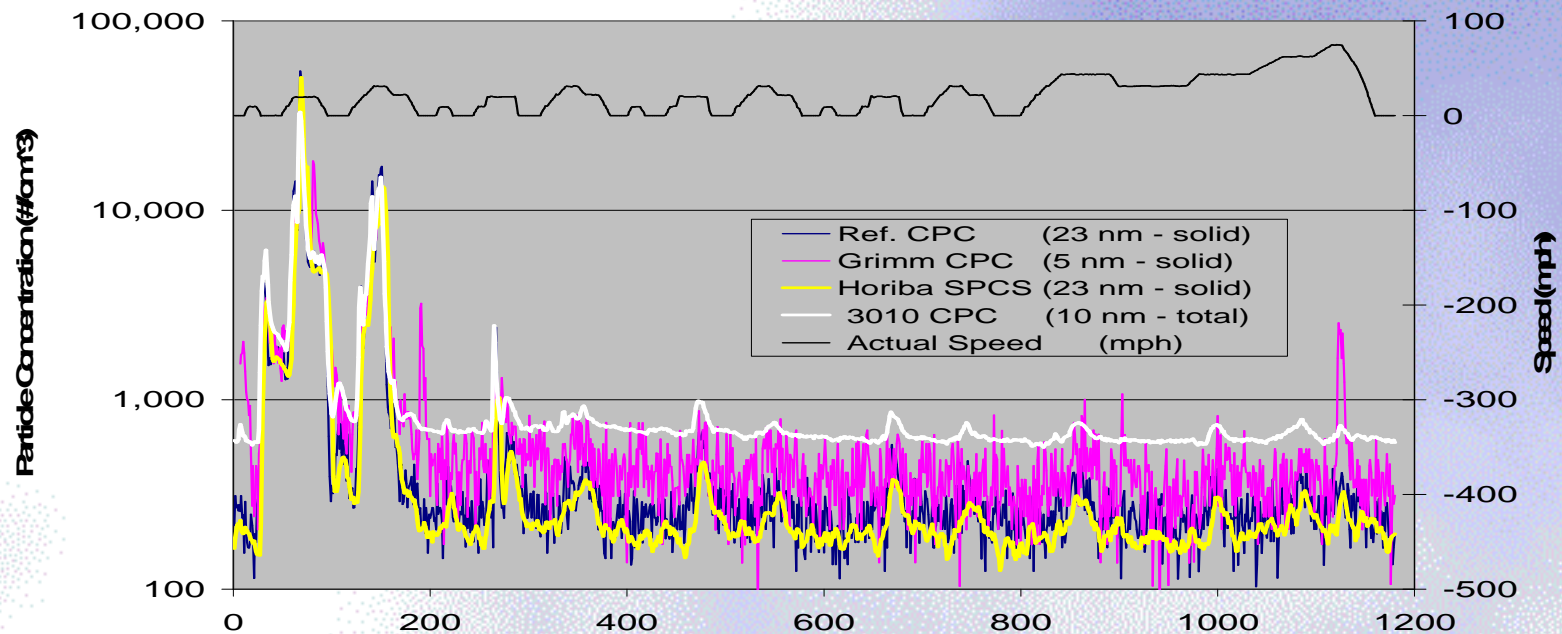


- All four particle counters are comparable to each other.
- Solid Particles measured from the CARB Grimm CPC were about 20% higher than the PMP compliant CPCs. Those particles could be sub-20nm solid particles
- The EEPS results were almost three times higher than the other particle counters due to higher instrument noise.



# Emission Results (cont')

## 3. Real-time Particle Number Concentrations during NEDC Cycle: PNCs

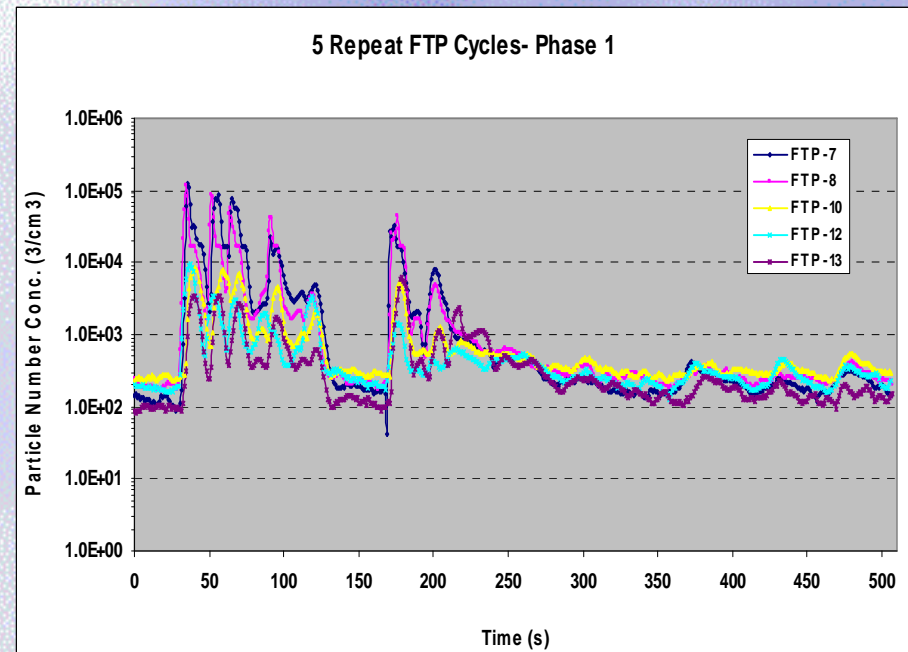
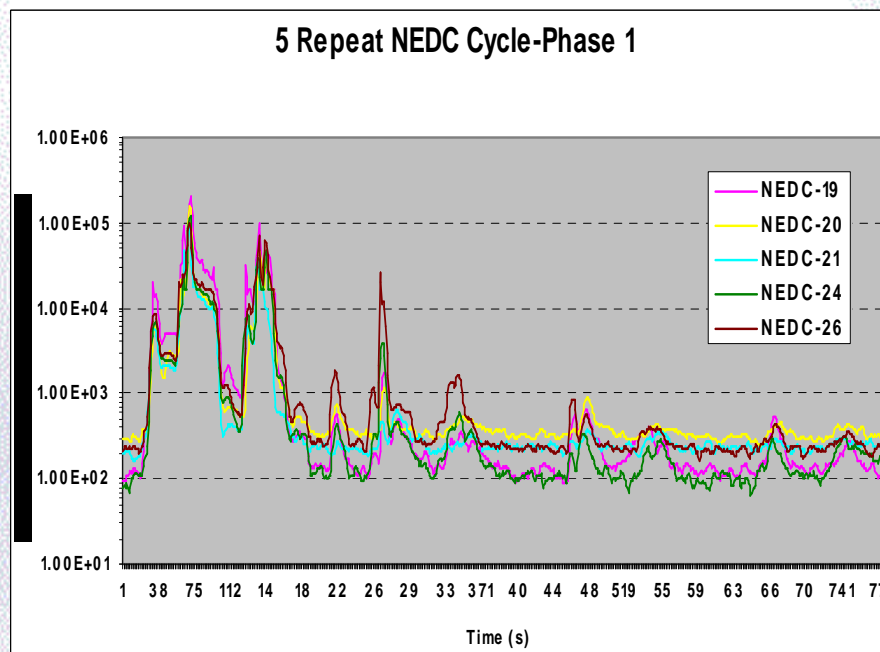




# Emission Results (cont')

## 4. Repeatability of Particle Number Counting System:

- Horiba SPCS in Five Repeat NEDC and FTP Cycles



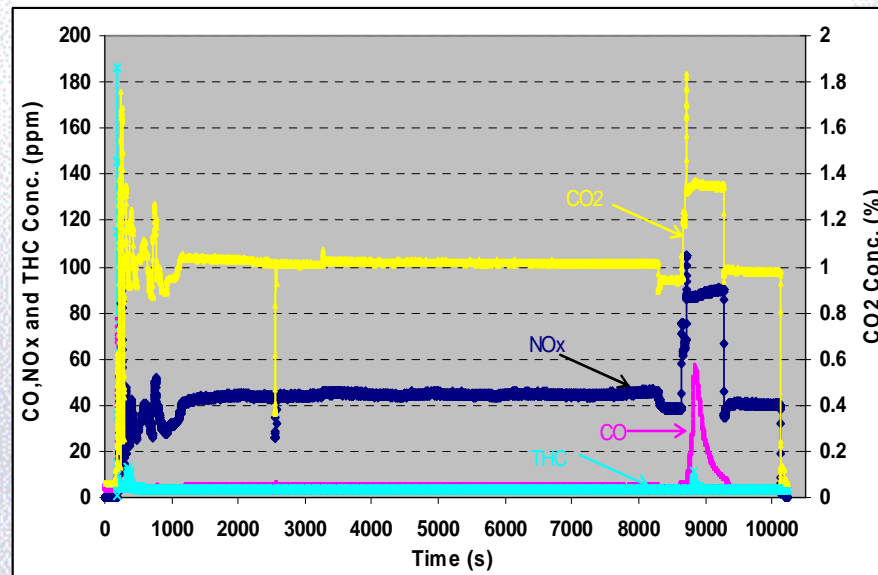
Particle number concentrations show similar trends and good agreement in five repeat NEDC and FTP cycles



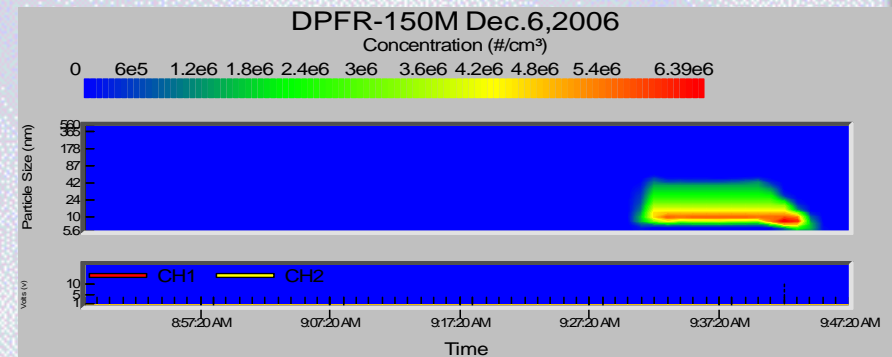
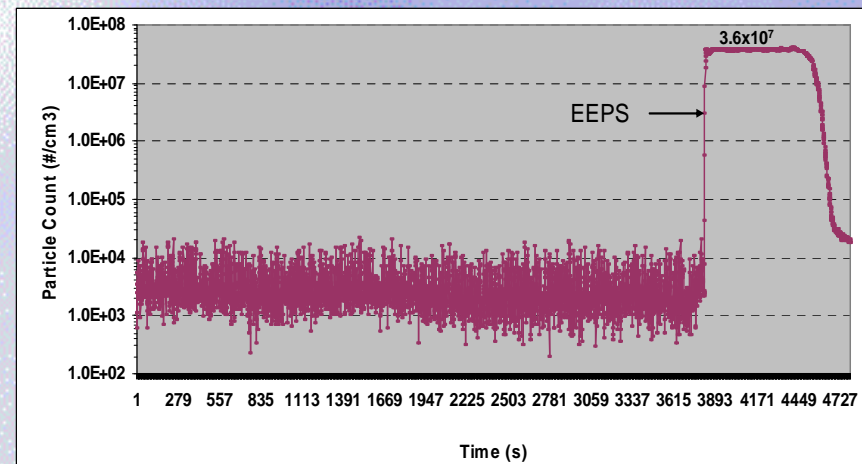
# Emissions Results (cont')

## 5. DPF Regeneration: During Steady-state cycle

### Gaseous Emissions



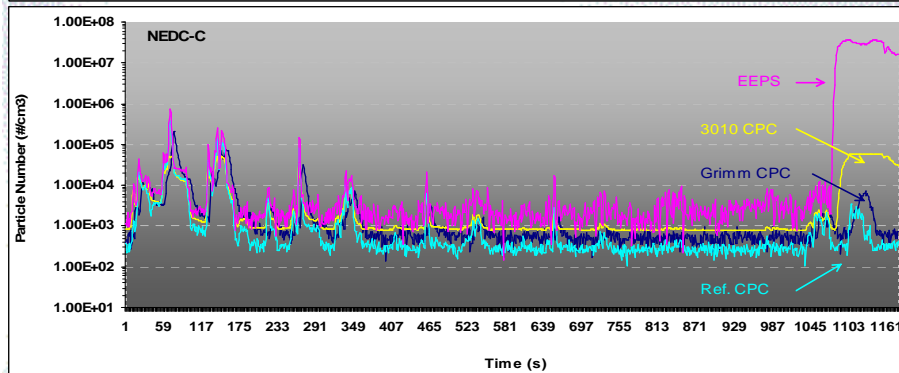
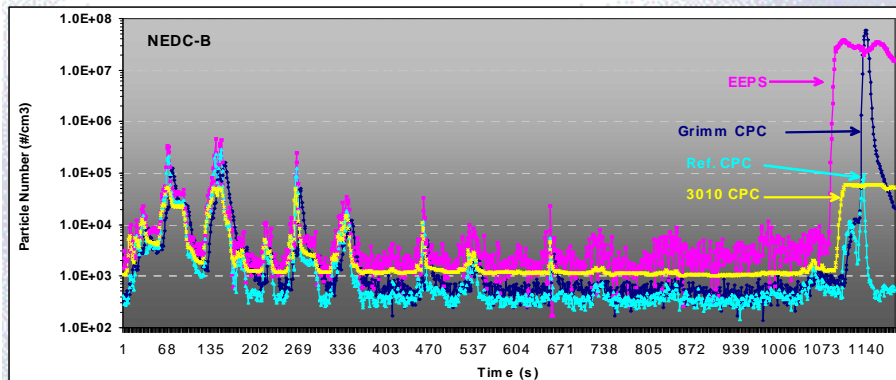
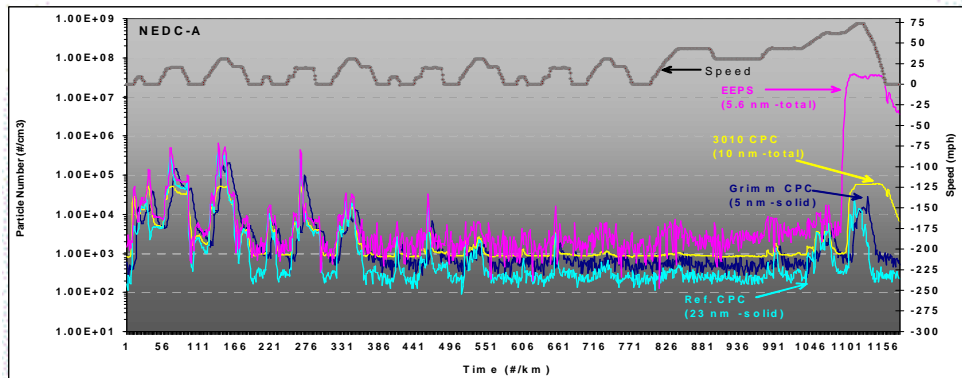
### Particle Number Emissions



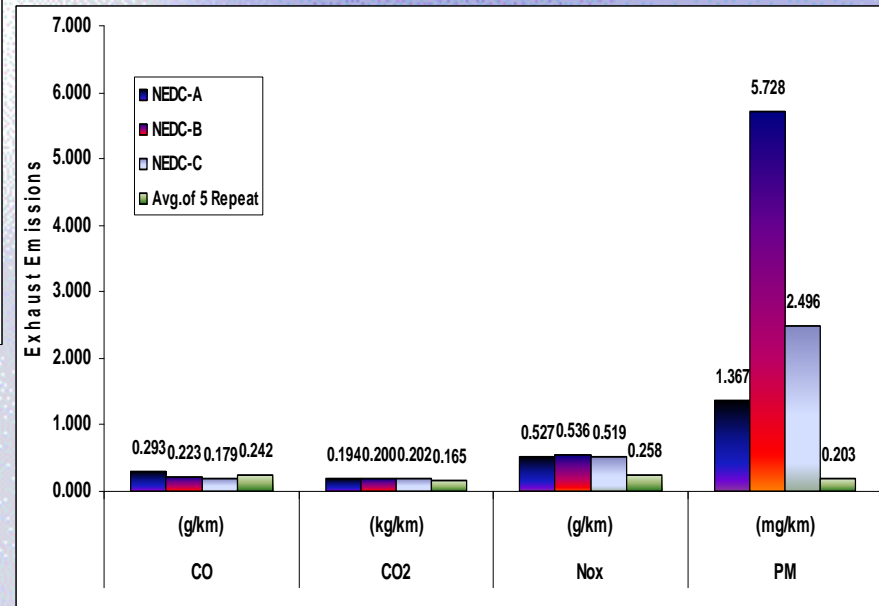


# 5. DPF Regeneration (cont')

- Particle Emissions in Three consecutive partial DPF regenerations during three NEDC cycles



Gaseous and PM Emissions:



- Particle emissions increase sharply during DPF regeneration and were measured by the EEPS and TSI 3010
- The PMP systems detected a moderate increase in particle numbers
- Grimm CPC measured higher particle numbers than PMP CPCs. Those particles could be either volatiles survived the VPR, or sub-20 nm solid particles emitted during DPF regeneration



# Summary

- This evaluation was valuable to both CARB and JRC to better understand particle count methodologies and measurement equipment.
- The PMP measurement method appears to be practical and repeatable to measure solid particle number emissions from engine exhaust.
- A more robust particle pre-conditioning system will enhance the reliability of the proposed methodology .
- Alternative particle measurement systems such as the Horiba SPCS and CARB's measurement system are comparable to the PMP System.
- During DPF regeneration, nucleation mode volatile particles appear to be the dominant source of particles and several orders of magnitude higher than solid particles. The PMP measurement method does not account for these particles. Further investigation of volatile particle emissions is needed.
- Particulate mass and number emissions during DPF regeneration can contribute significantly to the overall cycle-average PM results depending on the frequency of regeneration. They should not be ignored. It is important to accurately quantify DPF regeneration emissions.
- Current particle counters can measure below 23nm and they should be considered because a significant portion of solid particles may below 23 nm.



# Next Steps

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- **Publishing the CARB final results**
- **Continuing to investigate measurement methodologies of ultrafine particles from light- and heavy-duty vehicles.**
- **Exploring the feasibility of participating in the Heavy-duty Engine PMP Program**

## References:

1. **A California Preliminary Assessment of PMP for Determination of Diesel Particle Emissions**  
Alberto Ayala, Sherry Zhang, Jorn Herner and William Roberson  
11<sup>th</sup> ETH International Conference on Combustion Generated Nanoparticles
2. **Is “Clean Diesel” the answer? (Is it both 'clean' and 'practically feasible'?)**  
Tao Huai, Jorn Dinh Herner, and Alberto Ayala  
Health Effects of Surface Goods Movement Symposium, University of California, Los Angeles
3. **Emissions Measurements from the Golden Vehicle – A Light Duty Diesel Vehicle Used During Validation of the European PMP Protocol.**  
Alberto Ayala, Sherry Zhang, Bruce Frodin, Jorn Herner and Whitney Leeman,  
17<sup>th</sup> CRC ON-ROAD VEHICLE EMISSIONS WORKSHOP
4. **Investigation of Ultrafine Particle Number Measurements from a Clean Diesel Truck using the European PMP Protocol**  
Jorn Dinh Herner, Alberto Ayala, William H. Robertson, Tao Huai  
SAE 2007-01-1114



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